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Low carbon electricity development in China—An IRSP perspective based on Super Smart Grid

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ABSTRACT

Low carbon electricity is essential for China's low carbon development. In the paper low carbon electricity is defined as an economy body manages to realize its potential economic growth fueled by less electricity consumption, which can be characterized by indexes of GDP electricity intensity and CO_2 emissions per unit electricity generation. IRSP is proposed by Hu [11] to implement power planning on state level in deregulated power sector and is used in the paper to study China's power planning into 2030. A business-as-usual scenario is projected as baseline for comparison while low carbon electricity development based on IRSP is studied. Results show that, with IRSP, China could save energy by 1.5 billion toes and reduce CO_2 emission by 5.7 billion tons, during 2010–2030. Super Smart Grid (SSG) must be constructed as the physical foundation of IRSP. The main components of developing SSG in China are discussed.

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Contents

1. Introduction

China is the second biggest energy consumer and the biggest greenhouse gas (GHG) emitter in the world. Currently, China is right in the rapid process of industrialization and urbanization. Economic growth will keep at high speed for at least twenty years, which implies the unavoidable immense energy demand and the accompanied GHG emissions [1,2]. Therefore one of the biggest challenges of sustainable development for China is how to respond to climate change and reduce GHG emissions [3,4].

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As pointed out by President Hu Jintao, climate change is fundamentally a development issue. Hence neither stopping the development to deal with climate change nor developing the economy without considering the climate change is acceptable [5]. During 1980–2005 periods, electricity generated by coal accounts for 80% of total electricity supply and contributes around 40% of total GHG emissions in China. In order to explore a suitable path for low carbon economy [6], low carbon electricity development is essential for China.

In order to realize low carbon electric power sector development in China, on supply side, China has to actively exploit carbon-free renewable energy including nuclear, wind, solar and others and significantly raise the ratio of renewable power generation in total power supply. On the same time, China must increase the unit capacity of thermal plant to decrease CO_2 emissions from thermal power generation. On demand side, China must enhance energy utilization efficiency and lower electricity demand substantially. In fact, China has taken "energy conservation priority" policy as state policy even since 1980th. When crafting power supply planning for the future, China must consider both supply and demand side resources. Integrated Resource Planning (IRP), which considers both supply-side and demand-side options, has been a useful planning process for power supply planning when the electric power industry was dominated by regulated and vertically integrated utilities. However, the effectiveness of IRP is gone because of the restructuring of power sector in China. Meanwhile the power grid must be strong and smart enough to incorporate large-scale distributed renewable power generation on supply side and to encourage energy efficiency and conservation on the demand side.

The paper is an attempt to study China's low carbon electricity development into 2030 in an integrated resource strategy planning (IRSP) perspective. Section 2 gives the overview of power sector in China. Section 3 discusses the concepts of IRSP and efficient power plants (EPPs) and the main sources of EPPs in China. Section 4 deals with an IRSP perspective of low carbon electricity development in China. A low carbon scenario is projected for comparison with a business-as-usual scenario to manifest the energy conservation and GHG reduction potential in China's power sector. Section 5 deals with the Super Smart Grid (SSG) which can implement low carbon electricity development in China. The main components of SSG will be discussed in this section. Section 6 discusses the concept of low carbon electricity. Finally Section 7 is the conclusion.

2. Overview of power sector in China

Even since 1990th, installed generation capacity and total electricity consumption has increased quickly to catch up with the economic growth. Installed generation capacity increased from 137.9 GW in 1990 to 863.6 GW in 2009 while total electricity consumption increased from 612.6 TWh to 3658.7 TWh [7] (Fig. 1).

China is rich with renewable energy endowment. The total prospective reserve of hydropower in China is 700 GW, among which 390 GW is technologically viable. Of all the technologically viable reserve, 125 GW is small hydropower with installation capacity less than 25 MW which has little negative impact on environment and ecology. Considering wind power, onshore and offshore together, according to anemometry, on 10 m altitude, the theoretical wind power resource in China is 1000 GW while on 50 m altitude it is 2000–25,000 GW. The theoretical solar resource exploitable in China is around 1700 billion ton coal equivalent (tce) every year. For more than 2/3 land area, there is 2200 sunshine hours above 5000 MJ/m^2 heat radiation throughout the year. According to estimate, if 85.14 million km^2 desert was used for solar power development, the electricity generated could amount to 128,000 TWh annually. Available biomass energy resource including plant straw, wood residual, family and industry refuse etc. amounts to 600–700 million tce, if used for power generation, can produce 1500–1750 TWh electricity annually. China has formulated favorable policy for renewable energy development. Ever since the *Renewable Energy Law* formulated in 2005 and the *Medium-and-long Term Development Planning for Renewable Energy* in 2007, renewable energy has been witnessed rapid growth in China [4,8]. From 1990 to 2009, hydropower increased from 79.3 GW to 196.8 GW, nuclear power increased from 2.1 GW to 9.1 GW and wind power from 0.3 GW to 16.1 GW, totally accounting for 25% of generation capacity in 2009. Planning of seven wind power bases with prospect 100 GW capacity installations has been approved in 2010. In 2008, hydro, nuclear and wind power accounts for 8.9% primary energy consumption, which is 3.8% point higher than that in 1990 (Table 1).

Measured by the ratio of electricity consumption to terminal energy consumption, electrification level in China has been improved from 9.1% in 1990 to nearly 20% in 2009. Because electricity is the most efficient and convenient way of energy utilization, increase of electrification level has contributed significantly to the gross energy efficiency improvement in China. GDP energy intensity has been decreased by 54% from 1990 to 2009. Electricity utilization efficiency has also experienced obvious improvement during the electrification process. GDP electricity intensity, measured by electricity consumption per 10,000 yuan GDP (in 2005 year constant price) has been decreased from 1431 KWh in 1990 to 1280 KWh in 2009. Power generation efficiency also experienced improvement during the period. In 1990 the coal consumption for coal-fired power plant to generate one KWh electricity was 390 gram of coal equivalent, while it was 370 in 2005 and 339 in 2009. CO_2 emission of unit power generation in China decreased from 0.85 ton in 1990 and 0.755 ton in 2005 to 0.70 ton in 2009.

3. Integrated resource strategy planning

3.1. Concept of integrated resource strategy planning (IRSP)

With the Oil Crisis of the 1970s, increased land cost and the heightened environmental pressures, the troublesome power utilities in the United States began to re-think how to minimize the cost of power supply. The theory and practice of Integrated Resource Planning (IRP) and Demand-side Management (DSM) were emerged as a result [10]. IRP challenged the traditional idea of resource planning in which, adding new Traditional Power Plants (TPPs) is the only way to satisfy demand growth. The minimization of power supply was achieved through optimization on both demand and supply sides in IRP.

IRP is feasible when power industry was dominated by regulated and vertically integrated utilities. However, its effectiveness was largely deprived due to the restructuring of power sector in China and elsewhere around the world in the later stages, where the selection and investment in generating facilities were left to the unregulated market and regulated power grid utility is incapable to run IRP. Worldwide experiences have proved that DSM is useful on energy efficiency on the consumer side and could be the first priority in face of climate challenge. Integrated Resource Strategic Planning (IRSP) was proposed to replace IRP in a deregulated power sector meanwhile elevated IRP to national level [11–13].

IRSP integrates and optimizes various supply-side resources such as thermal, natural gas, hydropower, nuclear and wind power as well as demand-side resources through Efficiency Power Plants (EPPs). An EPP is defined as a device or a set of equipment that can save power consumption or avoid power plant investment and operation, including different applications as energy-saving lightings, high-efficiency motor systems, variable-speed drives,

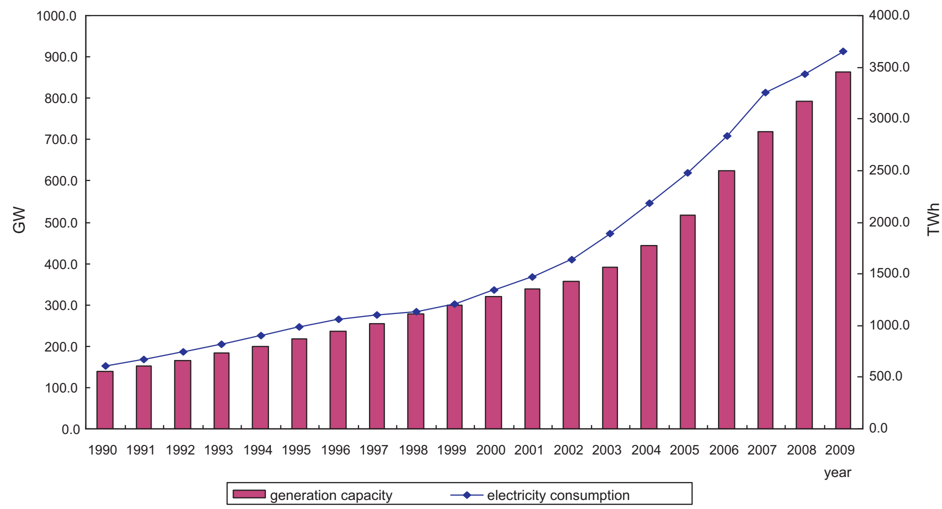

Fig. 1. Total generation capacity and electricity consumption in China during 1990–2009.

Table 1
Renewable energy resource and generation potential in China.

Renewable energy type	Available resource	Annual generation potential
Hydropower resource	390 GW (125 GW small hydro)	1700 TWh
Wind power resource	10 m high attitude: 250 GW (onshore) 750 GW (offshore);	2000 TWh (10 m)
	50 m high attitude: 2000–2500 GW	4000–5000 TWh (50 m)
Solar resource	1700 billion tce/annual (theoretical)	128,000 TWh (85.14 million km^2 desert)
	2200 sunshine hours with 5000 MJ/m^2 for 2/3 land area	
Biomass resource	600–700 Mtce/annual	1500–1750 TWh

Data source: [9].

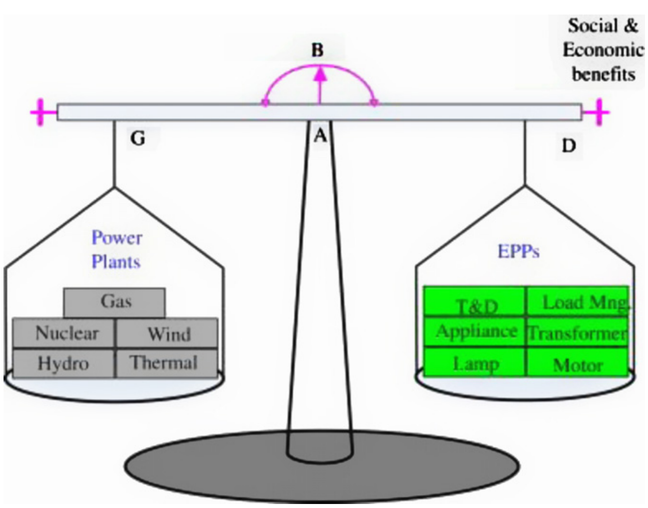

Fig. 2. Elements of IRSP model.

Fig. 3. IRSP model for power sector.

high-efficiency transformers, energy storage equipment, high-efficiency household appliances, as well as improving transmission and distribution efficiency and various load management measures. So EPPs can be considered as virtual power plants.

As is shown in Fig. 2, IRSP model has four major components: EPPs on the demand-side, TPPs on the supply-side, economic benefits and social benefits. The newly installed power generation capacity in Fig. 3 can include both of EPPs and TPPs. Maximum economic and social benefits could be achieved through adjusting TPPs and EPPs via appropriate policy mix such as electricity price and subsidies. Under deregulated environment only the Government has the ability to create favorable policies for EPP. Thus, it is the duty of Chinese government to design optimum market mechanism and incentive policies to promote EPPs on the demand side and promote clean energy generation on the supply side, thereby achieving energy conservation and emissions mitigation goal.

3.2. Main components of EPPs in China

Resources in the electricity demand-side for EPP consist of two areas: load management and energy efficiency management. Load management seeks to reduce peak load demand, while energy efficiency management seeks to save energy through the use of advanced energy technology and improved efficiency. Though the electricity intensity of some products in China has reached the advanced international levels, there are still great opportunities for efficiency improvements (Table 2).

Table 2
Comparison of energy indicators of selected products (2006).

Index	Unit	International advanced level	Chinese level	Efficiency improvement potential (%)
Comprehensive energy consumption of each ton of steel	Kilograms of standard coal/ton	642	741	15
Coal consumption of thermal power	Grams of standard coal/kilowatts	312	366	17
Comprehensive energy consumption of aluminum	Tons of standard coal/ton	14,100	14,795	5
Comprehensive energy consumption of pure soda	Kilograms of standard coal/ton	345	461	34
Energy consumption of unit oil refining	Kilograms of standard oil/tons	73	104	42
Comprehensive energy consumption of ethylene	Kilograms of standard oil/tons	786	1003	28
Comprehensive energy consumption of cement	Kilograms of standard coal/ton	102	156	53
Comprehensive energy consumption per box plate glass	Kilograms of standard coal/box	15	22	47

Source: The data is collected from various sources and calculated by the authors.

3.2.1. *Electricity savings in lighting*

Total electricity consumption for lighting was 411 TWh in 2008, about 12% of total electricity consumption in China. Savings in energy use and reduced demand can be achieved by improving greater efficiency in lighting systems. Around 60% of this is consumed by incandescent lamps and 40% by efficient lamps [14]. In 2008, about 15 billion lamps were produced, and about 10–20% of them were sold in China [15]. If the average utilization hour of a lamp is 2000 h per year, and if all the lamps last till their designed lifetime, the total capacity of the inefficient lamps would be about 124 GW, and the efficient lamps would be 83 GW in China. If 55% of the residents in China use fluorescent lamps as the Japanese do, and if all of the fluorescent lamps are substituted by electronic ballasts, 166 TWh of electricity can be saved. In order to promote efficient lamps, the Chinese government provides a 50% rebate to residential consumers and 30% to other consumers. Some local governments provide as high as a 90% rebate to residential consumers. This policy has been very effective in promoting green lighting in China.

3.2.2. *Improving motor system efficiency*

The electricity consumption of motors accounts for 60% of the total electricity consumption. Medium-and-large-sized motors account for 70% of the total motor capacity of 730 GW [16,17]. Improving the efficiency of medium-and-large-sized motors must be a high priority in DSM. Although a large amount of J-series motors were used in China before the 1980s, the government ordered the discontinuation of production of J-motors in 1984. The Y-series motor, which was developed in early 1980s, was 12% lighter than J-series and had a 30% higher starting torque. The extent of installation was comparable to international standards, but the efficiency ratio of Y-series increased by only 0.4%. Production of the Yx-series began in the late 1980s; it had 3% higher efficiency than the Y-series, and its efficiency ratio reached 92%. High-efficiency motors used in the United States have an efficiency ratio of 94.5%, which is 6% higher than the J-series in China. If only 30% of motors currently used in China were replaced by the most efficient ones, 39 TWh of electricity could be saved annually.

3.2.3. *Electricity savings in electric appliances*

Dramatic improvements in the Chinese standard of living have also created high demand for home appliances. Between 1985 and 2006, the penetration of electric refrigerators in cities and townships increased from 6.58 units to 91.75 units per 100 households. In rural area, it increased from 0.06 units to 22.48 units per 100 households. The penetration of television (TV) sets in cities and townships increased from 17.21 sets to 137.43 sets per 100 households, while in rural areas it increased from 11.74 sets to 106.88 sets. Between 1995 and 2006, the penetration of air conditioners in cities and townships increased from 8.09 units to 87.79 units per 100 households, while in rural areas it increased from 0.18 units to 7.28 units. Residential electricity consumption is projected to reach 500 TWh in 2010. If only 10% savings were realized, the potential in this sector could exceed 50 TWh annually.

3.2.4. *Transformers*

Currently in China approximately 40% of the total loss in the transmission and distribution systems occurs in transformers. Chinese power transformers that are widely used are the S6, S7, S9, and S11 transformers. These are three-phase oil-immersed power distribution transformers. “S” is a short name for “three-phases” and is adapted from the Chinese pronunciation for “three.” The numbers after the S are the series numbers. The larger a series number, the more efficient is the equipment. Based on statistics from 2004 [18], the total capacity of Chinese transformers was 2.77 TVA, and about 10% of this capacity consisted of the inefficient S6 and S7-series transformers. Promoting energy efficiency in transformers requires replacing inefficient transformers with efficient ones. For example, replacing S7 and lower series transformers with S9 or S11 series transformers can decrease line loss by 10–20%.

3.2.5. *Load management potential*

China’s impressive experience with load management provides a solid foundation for load management to continue to help address power shortages and to allocate system resources efficiently over time. The benefits of load management are evident during power outages. Load management will help avoid involuntary outages and the heavy costs incurred during power supply disruptions.

For many regional grids, there are only about 100 h of peak load that exceed 90% of the annual peak load. For example, in 2001, there were only 24 h of peak load that exceeded 95% of the annual peak load of the Beijing Grid, and there were 93 h of peak load that exceeded 90% of the annual peak load. A simulation study [19] shows that improving load factor in China by 1% in 2003 could have saved more than 6 million tce by improving the operation of power plants, assuming that total energy consumption did not rise. Thus, load management efforts can also provide efficiency gains. As economy grows and electricity consumption in commercial and residential sectors rises, load factors will tend to decrease. For these reasons, load management should continue to play an important role in DSM in China.

4. IRSP perspective of low carbon electricity development in China

4.1. *BAU scenario*

In next 20 years China will undergo the middle-and-later period of industrialization and the economy is expected to grow with fast pace. GDP would reach 61.59 trillion RMB in 2020. At that time, China will accomplish the process of industrialization and step into post-industrialization stage. Afterwards, GDP is expected to grow with annual growth rate of less than 6% and would reach 105.21 tril-

Table 3
Electricity demand under BAU scenario.

	Year	Electricity demand (TWh)	Electricity intensity (kWh/1000RMB)	Per-capita electricity consumption (kWh/person)
History	1980	295.43	1676	299
	1985	405.13	1382	408
	1990	612.60	1431	606
	1995	988.64	1295	874
	2000	1350.85	1171	1089
	2005	2484.82	1290	1911
BAU projection	2010	4055.96	1279	3004
	2015	5628.44	1271	4049
	2020	7502.84	1218	5174
	2025	9514.11	1160	6700
	2030	11,091.13	1054	7922

Note: The history data is sourced from CEC [7] and NBS [20] and projection is calculated by the authors.

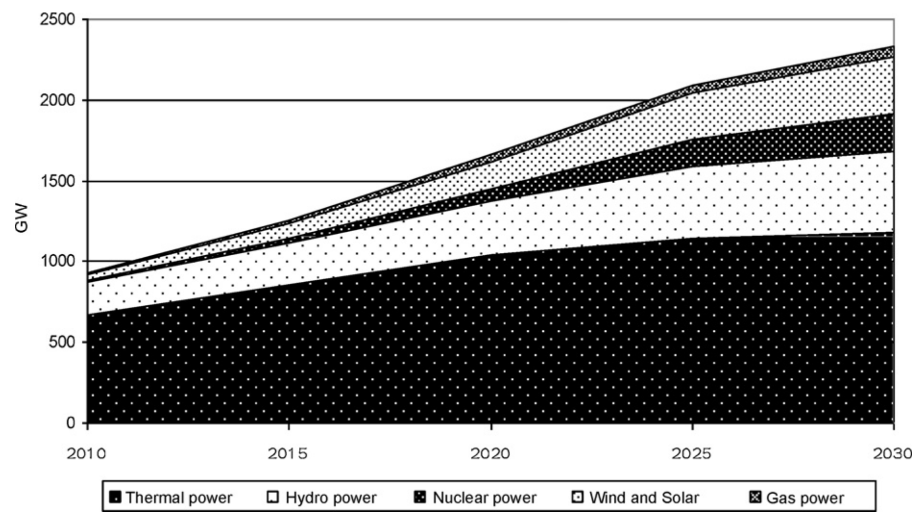

Fig. 4. Integrated resource strategic planning for power sector in China, 2010–2030.

Table 4
Clean generation and capacity.

Year	Clean generation		Clean generation capacity	
	(TWH)	The share (%)	(GW)	Share (%)
2010	646.23	16.75	221.21	26.56
2015	1119.3	19.91	382.39	30.57
2020	1948	25.38	593	35.5
2025	3011.6	32.94	900	43.05
2030	3887.13	37.19	1091.24	46.78

lion RMB in year 2030. Electricity demand would also experience swift growth to catch up with economic growth. It would reach 7502.8 TWh in 2020 and 11,091.1 TWh in 2030. In the BAU scenario, power generation capacity should be 1720 GW in 2020 and 2470 GW in 2030 (Table 3).

4.2. Low carbon scenario based on IRSP

According to the idea presented in Section 3 and according to the model presented in Hu et al. [12,13], Power generation capacity in China during 2010–2030 periods is projected in Fig. 4. In 2020, clean energy generation capacity (hydro, nuclear, wind and solar power) would amount to 593 GW, accounting 35.5% of total generation capacity and clean generation would amount to 1948 TWh, accounting for 25.38% of total generation. In 2030, clean energy generation capacity would amount to 1091 GW, accounting for 46.78% of generation capacity, and clean generation would amount to 3887 TWh, 37.19% of total electricity generation (Table 4). With EPP, 142 GW generation capacity would be avoided and 285.59 TWh electricity would be saved on demand side in year 2020. In year 2030 EPP capacity would amount to 277.37 GW and save electricity by 783.46 TWh. Hence during 2010–2030 periods, 274.23 million toe primary energy could be saved and about 676.87 million ton CO_2 emissions be reduced (Table 5).

5. Developing Super Smart Grid in China

On the transmission side Super Grid can take advantage of renewable and clean power generation in a long distance and integrate huge amount of power generation into the grid. Smart Grid (SG) on the distribution side can stimulate customers to save electricity and sell their renewable power generation to the grid. Super Smart Grid (SSG) has been studied to integrate both smart grid and super grid for energy conservation and renewable energy utilization in Europe [21]. However "Smart grids" do not enjoy a commonly accepted definition in the power planning literature.

Table 5
EPP and related energy conservation and CO_2 mitigation.

Year	Efficiency power plant (GW)	Electricity saving (TWh)	Energy saving (Mtoe)	Mitigating emission CO_2 (Mton)
2010	14.6	11.91	4.17	10.3
2015	46.72	78.58	27.5	67.93
2020	142	285.59	99.96	246.88
2025	204	491.28	171.57	424.16
2030	277.38	783.46	274.23	676.87

Table 6
Key components of developing SSG in China.

Aspects	Key components
Power generation	Wind power grid-access technology
	Solar power generation and grid-access technology
Power transmission	Advanced power transmission technology
	Smart grid dispatch technology
Power distribution	Distributed generation and mini-grid technology
	Step-down transformer technology
	Advanced voltage control technology
Power utilization	Power consumption information feedback technology
	Smart-building power conservation diagnosis and metering technology
	Energy efficiency and demand side response management technology
	Electric car charging load management technology

Some of the countries have devised diverse blueprints for the development of SSG according to their specific national conditions and characteristics of power grid. For instance, the United States addresses retrofitting existent grid infrastructures, promoting clean energy and wide use of Plug-in Hybrid Electric Vehicles. The European Union attaches much importance to such issues as optimizing both grid facilities and their operation and management, and enhancing the competence of grid to accommodate the integration of renewable resources [22]. In Japan, SSG is focused on addressing the problems incurred by the introduction of large-scale dispersed PV power. Thus, for the purposes of this paper, Super Smart Grid is defined as a power grid system that will economically accept and transmit renewable power from the supply-side and operate efficient power plants from the demand-side. According to our study, SSG can be combined with IRSP to identify the costs and benefits for the following possible practices: (1) promote clean energy use to reduce fossil energy consumption; (2) improve generation efficiency and energy use efficiency to reduce coal consumption; (3) enhance transmission efficiency of the grid to reduce electricity line losses; and (4) improve end use energy efficiency to promote the use of EPPs. Hence SSG is a complicated system including power generation, transmission, distribution and the utilization of customer resources. The following components are essential for developing SSG in China (Table 6).

6. Discussions on low carbon electricity

Low carbon electricity (LCEl) is a process of searching Pareto's improvement, i.e. reducing electricity demand on demand side and mitigating emissions on supply side to meet the requirement of economic growth, which can be intuitively interpreted by Fig. 5. It implies that if the potential GDP for a country is g, the corresponding power demand under BAU scenario would be pe. By implementing IRSP, the economy manages to realize g with power demand pe′ (pe > pe′). In this case it is defined that the power sector is in a way of LCEl. In other words, if an economy body manages to realize its potential economic growth fueled by less power consumption, then it is in a way of LCEl. It can be characterized by GDP electricity intensity and emissions per-unit of power generation. If they are decreased for a country, then, the country's power system is in the way of LCEl and vice versa.

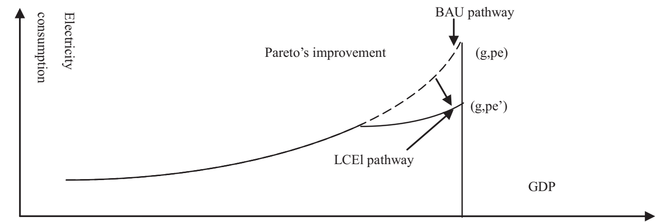

Fig. 5. Intuitive explanation of low carbon electricity (LCEl).

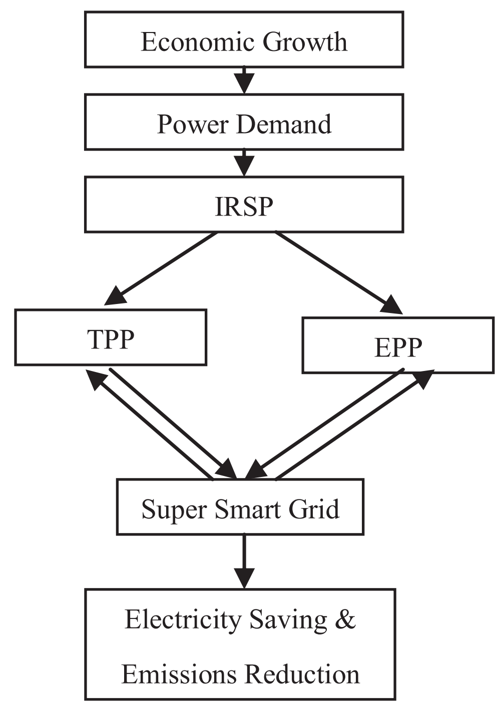

Fig. 6. Low carbon electricity in China.

During 1990–2009 periods, the electricity intensity and the CO_2 emission of unit power generation in China was 89.4% and 87% of that in 1990 respectively. Thus power sector in China was in a way of LCEl during 1980–2005. During 2010–2030 periods, electricity intensity would decrease from 1279 to 1054 KWh, while CO_2 emission of unit MWh electricity generation in China would decrease from 0.70 to 0.52 ton, thanks to efficiency improvement and energy structure enhancement. Therefore with IRSP and SSG China could still adhere to LCEl in the future.

IRSP and SSG will save energy and mitigate emission on both power generation and consumption sides, therefore constituting the core of LCEl in China (Fig. 6).

7. Conclusions

Low carbon electricity development is essential for China to realize low carbon economy. In the paper, low carbon electricity

is defined when one economy manages to power the economic growth with less electricity consumed and less emission. Integrated resource strategic planning (IRSP), which could be used by the national government for long-term power planning, is used to study China's low carbon electricity development into year 2030. Results show that, with IRSP, China could save energy by 1.5 billion toes and reduce CO_2 emission by 5.7 billion tons, during 2010–2030.

Successful implementation of IRSP means it will be essential for institution building in the following aspects: (1) energy consumption audit and energy efficiency standards, especially in energy-intensive industries; (2) market-based financial incentives, including tax exemption, soft-loans, and green certificates to industrial stakeholders for investments in energy-efficient technologies; (3) incorporation of DSM into Electricity Law and other regulations to create a more predictable environment for DSM investments; and (4) proper incentive policy for promoting renewable energy development and utilization.

Besides institution reform, a strong and smart power grid is needed in physical sense to implement IRSP in China. Two thirds of coal, wind and solar power resource are located in western or west-northern China, four fifths of hydropower resource are located in west-southern China while two thirds power demand are located in east and midland China. The imbalance between resource and load center means that wide-scope, ultra-distant and high-capacity power transmission system is necessary for China. On the other hand, IRSP has to use advanced information technology to convert savings from energy efficient plants on the demand-side into power supply equivalents from power generation plants. Smart grids must be able to link energy efficient power plants on the demand-side with real power generation plants on the supply-side, and make these two kinds of power plants comparable. As such, if China wants to yield the greatest potential of IRSP, it is necessary to promote the construction of Super Smart Grid.

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